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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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The subscription price of the JOURNAL OF SEDIMENTARY PETROLOGY is $3.00 per year prepaid to addresses in the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, El Salvador, Bolivia, Colombia, Honduras, Nicaragua, Peru, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands.

Single numbers, $1.50 each.

Postage is charged extra: For Canada, 20 cents on annual subscriptions (total $3.20), and for all other countries in the Postal Union, 40 cents on annual subscriptions (total $3.40).

The JOURNAL will furnish reprints at cost. Orders should accompany corrected galley proof.

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GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PP. 103–124, FIGS. 1–19, TABLES 1–4, DECEMBER, 1940

THE RELATIVE RESISTANCE TO ABRASION OF MINERAL GRAINS OF SAND SIZE

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University of Minnesota, Minneapolis, Minnesota

ABSTRACT

Photomicrographs are presented that show the relative resistance to abrasion in running water of mineral grains of sand size. These represent the first of a series planned to cover the minerals that are commonly found in sedimentary rocks. Losses in weight of various size grades were observed and changes in the degree of sphericity of the mineral grains were determined.

The extent to which mechanical abrasion of mineral grains occurs during stream transportation of sediments has been discussed by numerous investigators, but quantitative data are limited mainly to studies of coarse sediments such as gravels, cobbles, and boulders. Wentworth (1919, 1931) plotted the results obtained from a study of cobble abrasion in a tumbling mill or drum, using various kinds of rock fragments. Daubree (1879) likewise experimented with rock and mineral fragments that slid over each other in a rotating cylinder. Marshall (1927) mixed materials of different dimensions derived from beaches in New Zealand, and found that the loss by abrasion of pebbles of hard rock amounted to 1.5 per cent in 24 hours, the travel during this time being equivalent to 24 miles. Cozzens (1931) conducted experiments in which tests were made in a mill on the loss of weight of large fragments of different minerals ranging in hardness on the Mohs scale from 2 to 9. Freise (1931) likewise, placed large mineral fragments in a huge rotating drum, and from the results of his experiments compiled a table showing the relative resistance to abrasion of a large group of common minerals.

In all of the studies referred to above, the ratio of amount of sediment to volume of water failed to approximate the natural stream environment. In most instances, such large quantities of sediment were used that the conditions in the abrasion drums more nearly approached those in a ball mill. Furthermore, quantitative data are not presented on sediments of sand size. Numerous generalizations based on isolated field observations have been published, but the conclusions are very inconsistent.

Because of the discrepancies that occur in the literature, the writer attempted to design an experiment in which the environment could be kept reasonably constant, and one in which a small quantity of fine-grained sediment could be subjected to abrasion in a large volume of water.

The data presented in this report are preliminary and include but a few of the minerals that are to be studied in various associations and combinations.

EXPERIMENTAL METHODS

Crushed and screened mineral grains were placed in a slowly revolving steel drum (fig. 1) that was geared to a velocity of 25 revolutions per minute. At this speed the velocity of the inner surface of the drum over which the mineral grains traveled, moved approximately 1.8 miles per hour. At this rate of speed, water in the drum flowed as a uniform current in the bottom part. No water other than that wetting the inner surface, was carried through a complete revolution of the drum. In fact, the inner walls of the ends of the drum remained dry above a dis-

tinct water-line. A partition in the plane half way between the ends of the drum, which are 10 inches apart, divides it into two equal compartments so that two charges may be tested at the same time without contaminating each other.

Fresh minerals were crushed and screened. Only the fragments that passed a 9-mesh screen and remained on the 16- and 32-mesh screens (openings approximately 1mm. and ½ mm. respectively) were used for the abrasion tests. Ten grams of each of the two screen sizes were placed in the drum and 3 liters of distilled water added. In order to compare the effects of abrasion on different minerals under similar environmental conditions, two or three minerals were mixed in the same compartment and allowed to abrade each other. When taken from the drum, they were separated by means of heavy liquids or by centrifuging.

For a preliminary test, compartment 1 of the drum was charged with 20 grams each of apatite, feldspar, and tourmaline and compartment 2 was given a charge of 20 grams each of quartz, hornblende, and garnet. Three liters of distilled water were added to each compartment, and the position of the water level marked on the inside of the drum. The drum was then rotated at the speed designated and the water in it flowed at approximately 1.8 miles per hour. Some water evaporated through the circular feeder windows in the ends of the drum. This was replenished every few days and the level kept at the 3 liter mark.

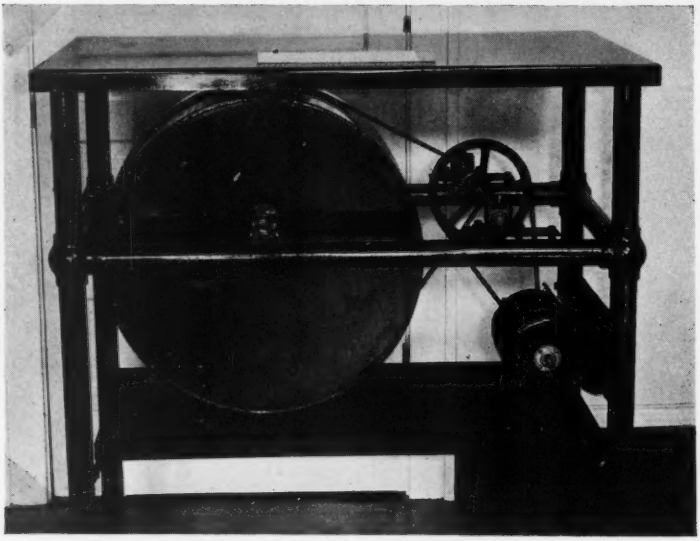

FIG. 1.—Mineral abrasion machine used in determining the relative resistance to wear, of mineral grains of sand size. The one foot straightedge placed on the top of the machine serves as scale.

RESULTS

At the end of 40 days when the current had traveled nearly 2000 miles the sediments in both compartments were sampled, separated, and photographed. Fig-

ures 2 to 13 show the amount of abrasion suffered by each. The quartz grains show very little change whereas the apatite is well rounded. The other minerals all show some effects of wear.

Since all of the mineral grains are small and the velocity of the water current is low, the wear is chiefly accomplished by abrasion. Impact and grinding, or battering and crushing, as defined by Marshall, play a secondary role. However, the presence of sharp, angular chips, (figs. 16–18) some of which are less than 1/16 mm. in diameter, indicate that impact may have played a part in removing small percussion fragments from the larger mineral grains.

TABLE 1. *Materials taken into solution during abrasion of mineral grains**

Dissolved Constituents	Compartment #1 Water plus apatite microcline tourmaline	Compartment #2 Water plus quartz hornblende garnet
	P.P.M.	P.P.M.
CaO	31.2	12.0
MgO	3.1	4.6
K_2O	26.4	5.2
P_2O_5	0.4	0.1

* The original charge was in the ratio of 60 grams of crushed mineral grains to 3 liters of distilled water. Dr. R. B. Ellestad, analyst.

After a total of 60 days of continuous flow, the drum was stopped and drained through bungs in the floor of the channel, and all mineral grains were washed from the floors of the compartments. The charge from each compartment was filtered and the filtrate analyzed for salts of calcium, magnesium, potassium, and phosphorus. (See table 1). Because of the development of iron rust on the lining of the drum, iron determinations were omitted. Appreciable amounts of calcium and phosphorus were added by the solution of apatite of compartment 1, and the microcline contributed considerable potash. Hornblende contributed most to the products of solution in compartment 2.

The residues were washed, dried, and screened. Table 2 shows the size distribution after 60 days of abrasion in water. The residues that were so fine that they remained in suspension after a settling period of two minutes were siphoned off and discarded.

After small samples of each fraction were retained for examination, the drum was recharged with the same mixtures in each compartment, and the abrasion continued for another 40 days, making a total of 100 days of continuous flow. This is the equivalent of nearly 5000 miles of travel. The loss by weight of the minerals, quartz, hornblende, garnet, and apatite, at the end of that period, is given in table 3.

TABLE 2. *Size distribution of mineral grains before and after abrasion in water*

Diam. in. mm.	Original Charge	Compartment #1 (Micro. Tour. Apatite)	Compartment #2 (Qtz. Hb. Garnet)	
	Wt. in gm.*	After 60 days Wt. in gm.	After 60 days Wt. in gm.	After 100 days Wt. in gm.
1	30.00	17.4	20.5	15.4
½	30.00	23.0	20.1	18.1
¼	0.00	3.5	4.0	3.1
⅛	0.00	1.5	1.0	.6
1/16	0.00	.4	.8	.3
−1/16	0.00		.7	.1
Total	60.00	45.8	47.1	37.6

* A total of one-half of a gram was removed from each compartment at the end of 40 days.

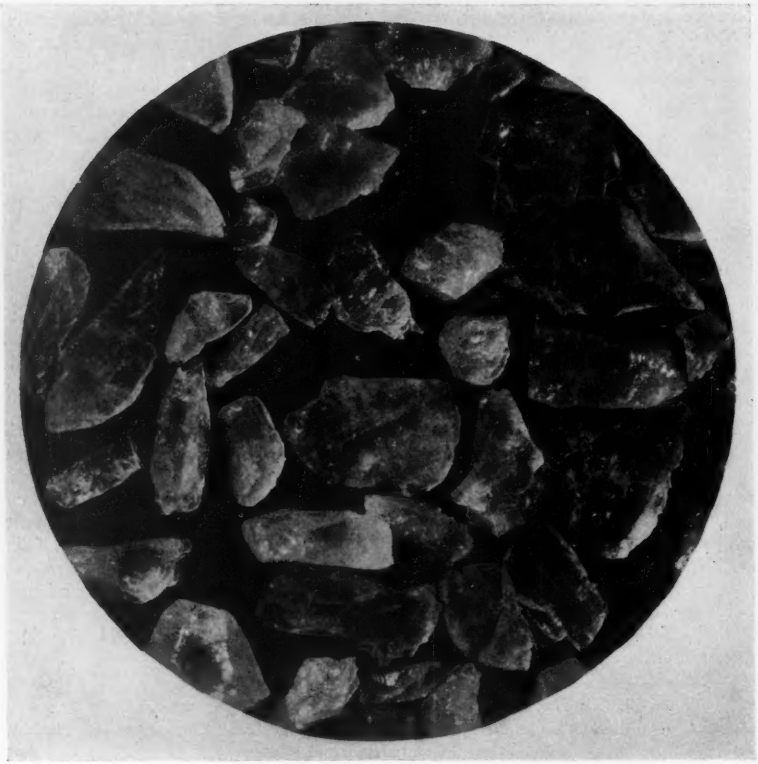

FIG. 2.—Vein quartz, freshly crushed, to pass screen with 2 mm. openings. On screens with 1 mm. and ½ mm. openings, ×10.

FIG. 3.—Quartz grains, same size as in Fig. 2, after 40 days of abrasion, ×10.

FIG. 4.—Microcline, freshly crushed, to pass a screen with 2 mm. openings. On screens with 1 mm. and ½ mm. openings, ×10.

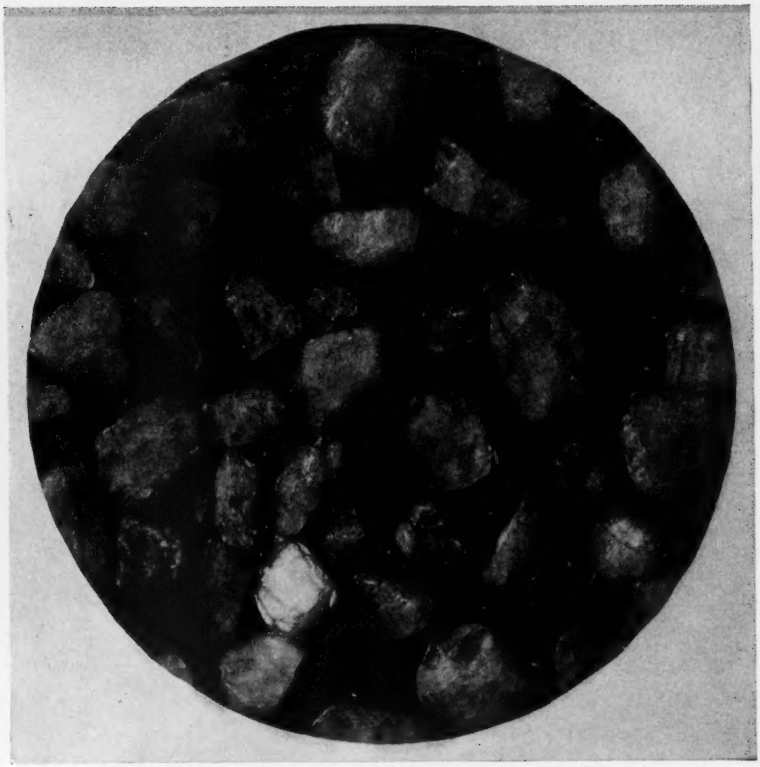

FIG. 5.—Microcline grains, same size as in Fig. 4, after 40 days of abrasion, ×10.

FIG. 6.—Apatite, freshly crushed, to pass screen with 2 mm. openings. On screens with 1 mm. and ½ mm. openings, ×10.

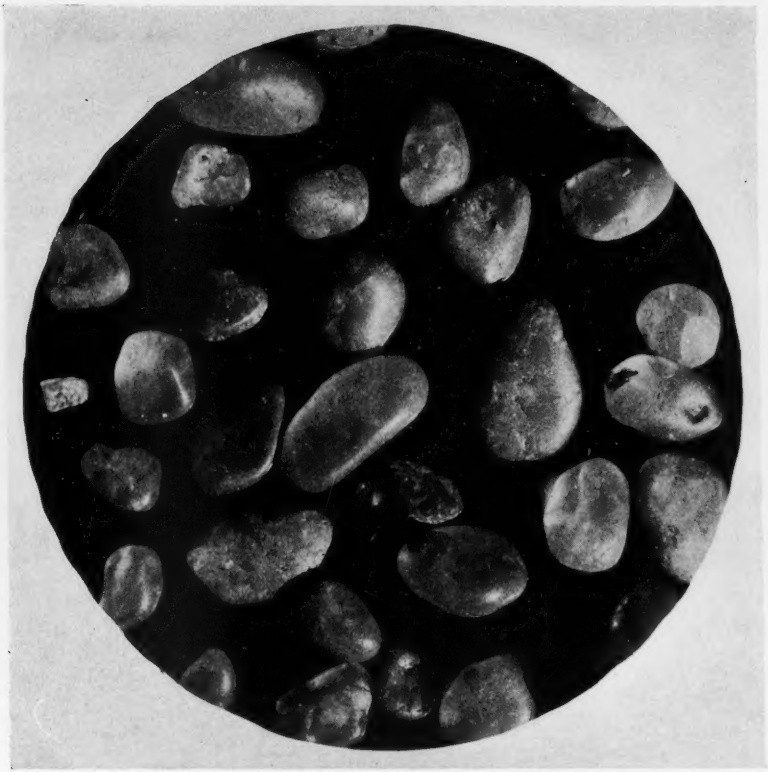

FIG. 7.—Apatite grains same size as in Fig. 6, after 40 days of abrasion, ×10.

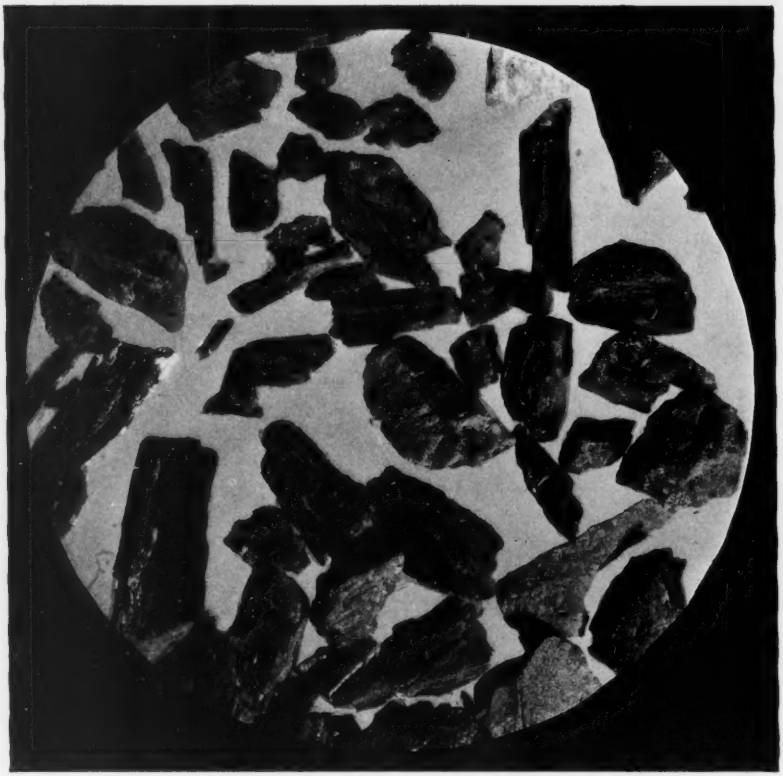

FIG. 8.—Hornblende, *freshly crushed, to pass screen with 2 mm. openings.* On screens with 1 mm. and ½ mm. openings, ×10.

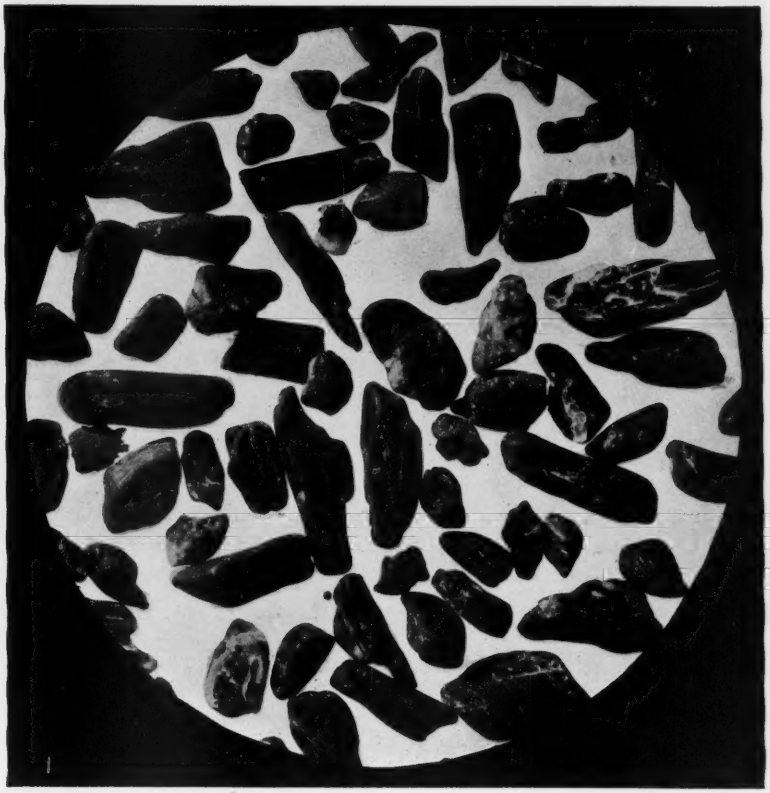

FIG. 9.—Hornblende grains same size as in Fig. 8 after 40 days of abrasion.

FIG. 10.—Garnet, pink, freshly crushed to pass screen with 2 mm. openings, and resting on screens with 1 mm. and ½ mm. openings, ×10.

FIG. 11.—Garnet grains same size as in Fig. 10, after 40 days of abrasion, ×10.

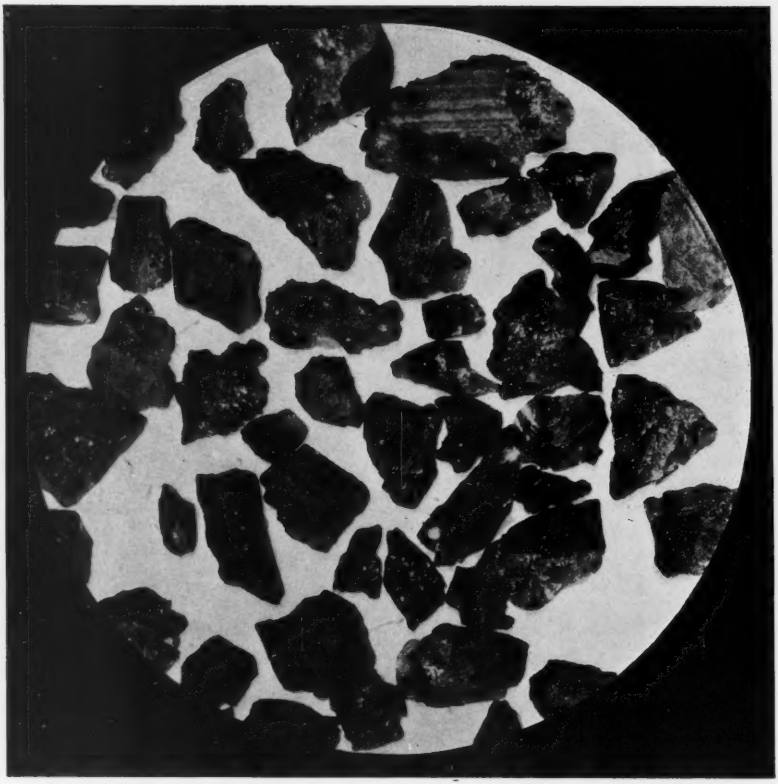

FIG. 12.—Tourmaline, black, freshly crushed, to pass screen with 2 mm. openings. On screens with 1 mm. and ½ mm. openings, ×10.

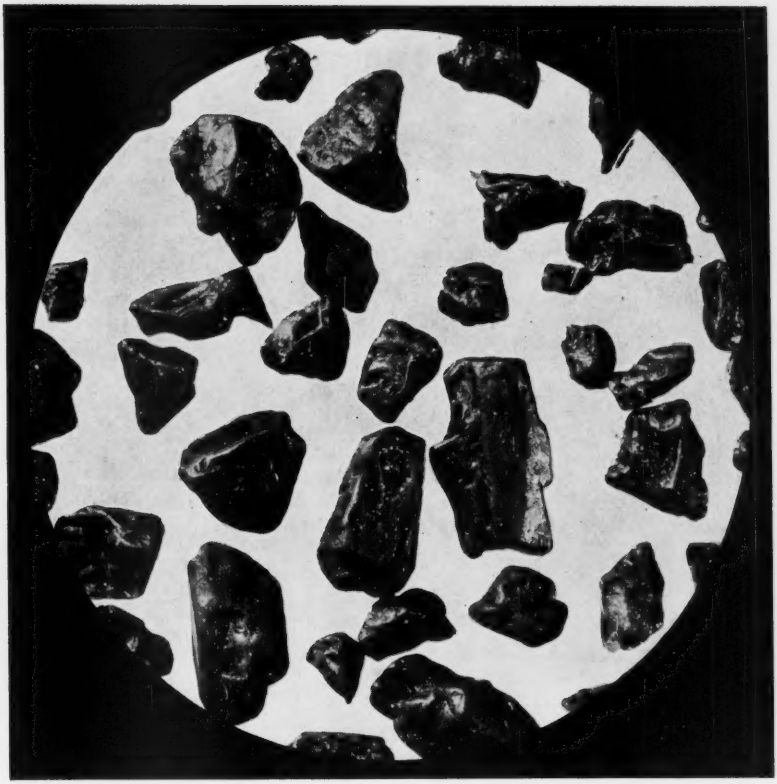

FIG. 13.—Tourmaline grains, same size as in Fig. 12 after 40 days of abrasion, ×10.

TABLE 3. *Percentages by weight lost from original weights of size grades during 100 days of abrasion**

Diam. in MM.	Quartz H. 7	Garnet H. 6	Hornblende H. 5.5	Apatite H. 5
2–1	24.2%	41.7%	82.2%	84.3%
1–½	22.4%	32.6%	57.4%	61.4%

* Corrections were made for the samples retained for study at the end of 40 days and 60 days respectively.

In comparing the losses of the various size grades, it must be remembered that when the grains of the coarsest fractions were abraded to smaller diameters they would pass the screen with 1 mm. openings and be added to those on the ½ mm. screen, whereas, there were no 2 mm. grains that might be reduced and join the residue on the 1 mm. screen.

The relative rate of wear may also be approximated by determining the *degree of sphericity* to which the individual mineral grains are abraded during their travel in the revolving drum. Figures 2 to 13 show the change in *roundness* produced in 40 days in the equivalent of 1800 miles of travel. The sharpness of the corners and edges have been noticeably reduced on all of the grains except those of quartz. Since many geologic factors as well as various properties of minerals are involved in the development of shape and roundness, no single measurement such as the degree of sphericity will serve as a safe criterion of rate of wear. Factors that influence such changes include crystal structure, hardness, cleavage, elasticity, various strength moduli, and others. However, since very little work has been done on mineral grains of sand size, a number of measurements were made to determine the degree of sphericity by abrasion on various grain sizes.

The degree of sphericity of the mineral grains was calculated by using Wadell's formula, $\phi = dc/Dc$, where dc is the diameter of a circle equal in area to the area obtained when the grain rests on one of its larger faces, and Dc is the diameter of the smallest circle that circumscribes

TABLE 4. *Relative changes in the degree of sphericity during abrasion*

Mineral	Diam. in mm.	Degree of Sphericity, $-\phi = \frac{dc}{Dc}$			
		Freshly Crushed	Period of Abrasion		
			40 days	60 days	100 days
Hornblende	2–1	.65	.69	.72	.78
"	1–½	.63	.67	.69	.76
Apatite	2–1	.74	.85	.87	.91
"	1–½	.74	.81	.83	.87
"	½–¼	.76	.80	.80	.81
Quartz	2–1	.72	.73	.75	.79
"	1–½	.70	.70	.71	.71
Garnet	2–1	.77	.77	.78	.80
"	1–½	.76	.763	.77	.77
Microcline	2–1	.67	.70	.72	.76
"	1–½	.65	.66	.69	.73
Tourmaline	2–1	.74	.76	.77	.79
"	1–½	.75	.76	.76	.77

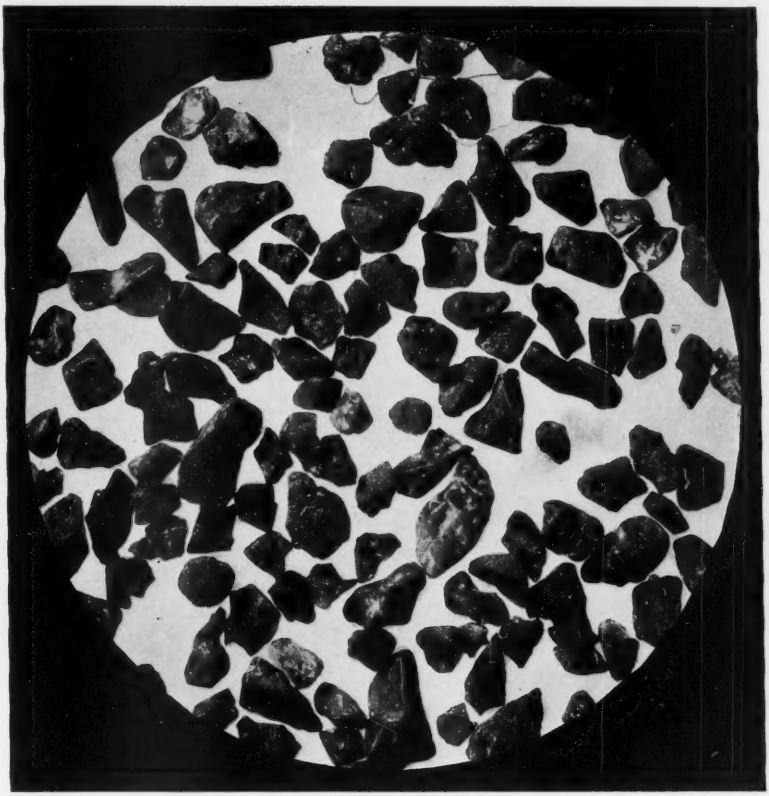

FIG. 14.—Tourmaline grains on screen with $\frac{1}{4}$ mm. openings, after 60 days of abrasion, ×10.

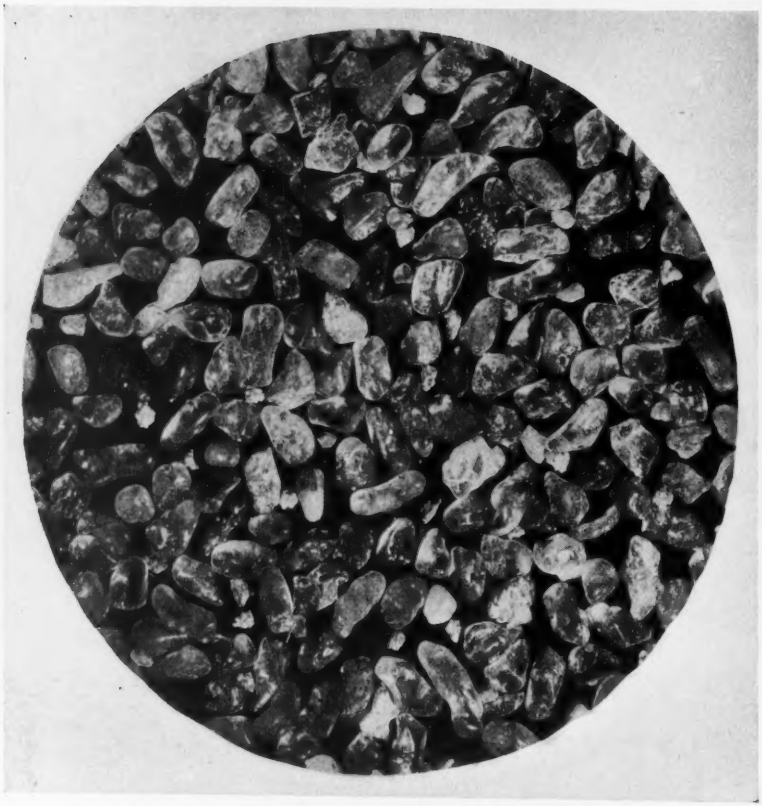

FIG. 15.—Apatite grains, $\frac{1}{2}$ to $\frac{1}{4}$ mm. in diameter, after 60 days of abrasion. Compare with Fig. 7, ×10.

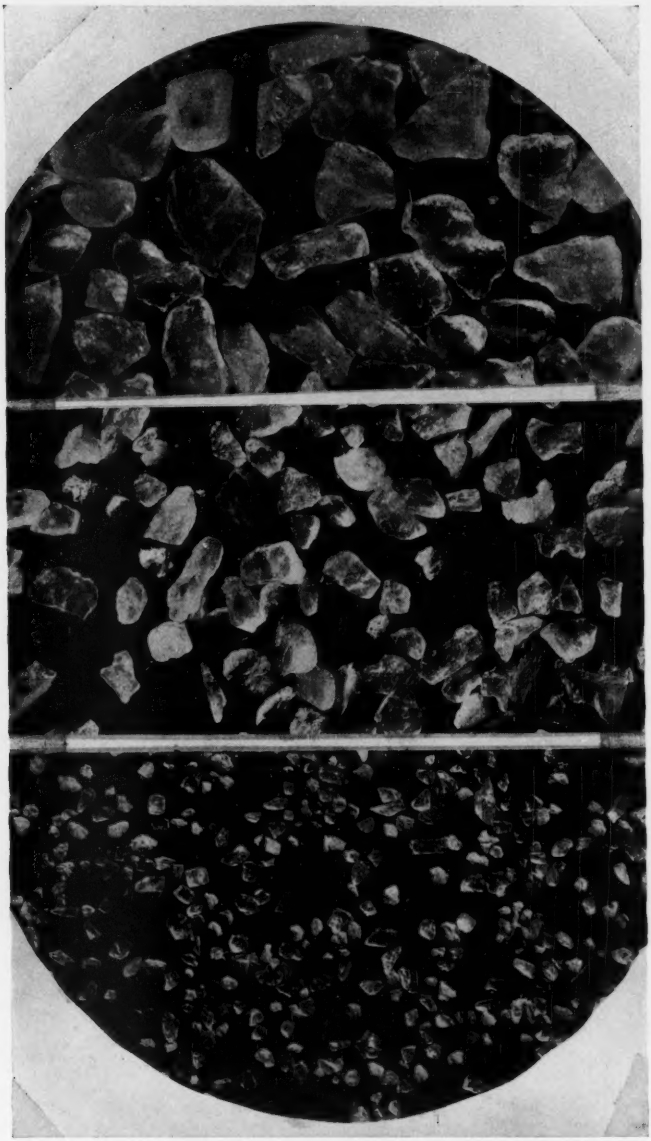

FIG. 16.—Quartz grains after 60 days of abrasion. Top, grains on ½ mm. screen. Middle, grains on ¼ mm. screen. Bottom, grains on 1/16 mm. screen. There were originally 1 mm. and ½ mm. grades, ×10.

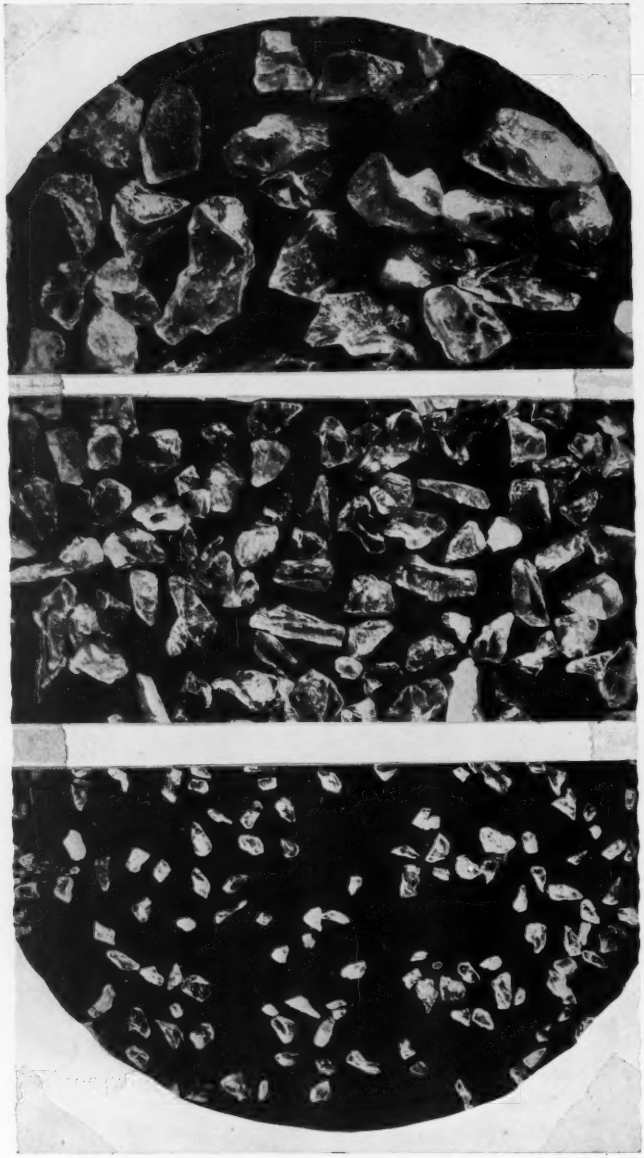

FIG. 17.—Garnet grains after 60 days of abrasion. Top, grains on ½ mm. screen. Middle, on ¼ mm. screen. Bottom, on 1/16 mm. screen. These were originally 1 mm. and ½ mm. grades, ×10.

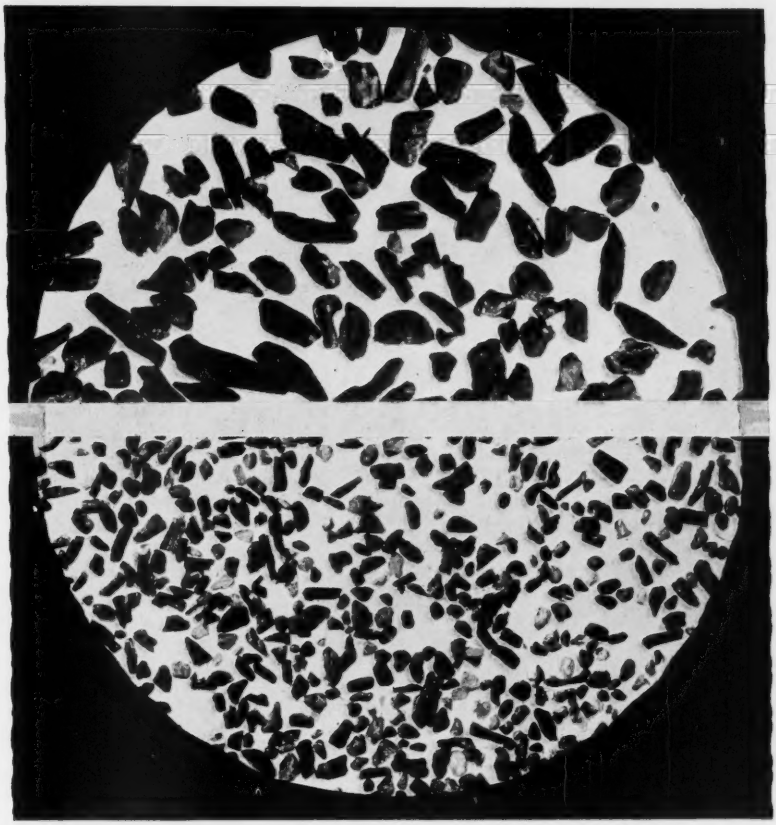

FIG. 18.—Hornblende and tourmaline grains after 60 days of abrasion. Top, grains *on* $\frac{1}{4}$ *mm. screen. Bottom, grains on 1/16 mm. screen. These were originally* 1 mm. and $\frac{1}{4}$ mm. grades, ×10.

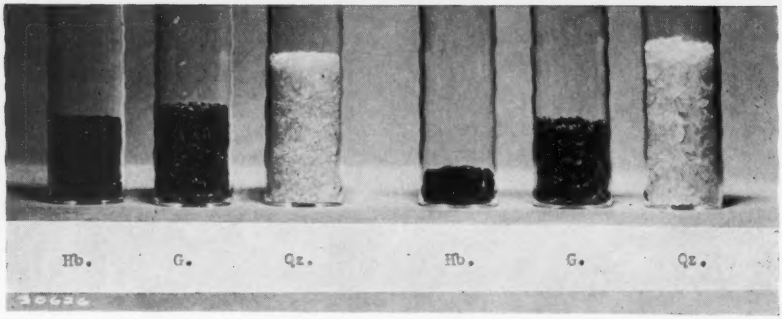

FIG. 19.—Vials with grains of hornblende (Hb), garnet (G), and quartz (Qz). The group to the right contains grains that are <2–>1 mm. in diam., those in the group at the left are <1–>½ mm. in diam. All three minerals were mixed together in the same compartment of the abrasion machine (Fig. 1) for 100 days. There were equal amounts of each mineral at the beginning of the experiment.

the outline of the grain. The values for *dc* and *Dc* were obtained by carefully splitting the samples with a microsplit. The grains were then mounted on a glass slide and their images projected and outlined on a drawing board. The area of each grain reproduction was then determined by a polar planimeter and from this value the nominal sectional diameter i.e., the diameter of a circle with the same area as the projection was computed. *Dc* was measured direct as the diameter of the smallest circle that circumscribes the reproduction of the grain.

From a study of figures 2 to 18 and of table 4, it is at once evident that the amount of abrasion on the small mineral grains is of a different order than that reported by Freise. He compared the resistance to abrasion of mineral fragments to that of hematite and established the following order: Hematite, 100; Orthoclase, 150; Quartz, 245; Apatite, 275; Augite, 420; Garnet, 420; and Tourmaline 950.

From Freise's tabulation, one would conclude that quartz and orthoclase are less resistant than apatite and that augite is nearly twice as resistant as apatite. However, when placed in the environment of the experiments outlined above which more nearly approximates that of the average stream, the writer finds that apatite is the least resistant to abrasion of the group of minerals tested to date and that it is also the most soluble. When listed in the order of increasing resistance, apatite is followed by hornblende, microcline, garnet, tourmaline, and quartz. In the various combinations of minerals abraded thus far, quartz has suffered the least amount of wear. Its comparative resistance is strikingly shown in figure 19.

More detailed measurements on the above minerals and on many other minerals will be reported at a later date.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PP. 125–135, FIGS. 1–2, TABLES 1–3, DECEMBER, 1940

HEAVY MINERAL ASSOCIATIONS IN QUATERNARY AND LATE TERTIARY SEDIMENTS OF THE GULF COAST OF LOUISIANA AND TEXAS*

MAX BORNHAUSER
Continental Oil Company, Lafayette, Louisiana

ABSTRACT

A study of the heavy mineral content of the younger Tertiary and Quaternary formations of the Gulf Coast of Texas and Louisiana shows that a considerable variation exists in the composition of the heavy mineral assemblages found in these formations. Mainly on the basis of these variations, it is possible to distinguish several well-characterized heavy mineral zones which are restricted to certain formations, and therefore serve as a means of identifying these formations, particularly in subsurface sections.

The study also establishes that there are two mineral provinces present in the Gulf Coast of Texas and Louisiana; one characterizes formations deposited in the Rio Grande embayment, the other, formations of the Mississippi River embayment.

Correlation of the heavy mineral zones and their relation to the surface and subsurface formations is shown in two cross-sections.

INTRODUCTION

The present paper summarizes the results of some heavy mineral investigations which the writer has conducted during the past few years in the Gulf Coast formations of Texas and Louisiana. These investigations were initiated with the purpose of testing the value of heavy mineral associations as a means for surface and particularly subsurface correlations. Although the investigations were extended over formations ranging in age from Claiborne (Eocene) to Pleistocene, the present discussion is limited to the heavy mineral assemblages in Miocene, Pliocene and Pleistocene formations. These are predominantly non-marine. They attain considerable thicknesses towards the coast, particularly in Louisiana. These heavy minerals contain numerous sand bodies, and they are well adapted for petrographic investigations of the type undertaken by the writer. Also, as separation of these formations in subsurface sections is difficult because of the absence of reliable lithologic and paleontologic markers, it seemed particularly desirable to investigate them and to search for additional means of differentiation and correlation. The formations under discussion and their main lithologic characteristics are shown in table 1.

The conclusions herein submitted are based on the examination of nearly one thousand subsurface and surface samples which are distributed over the entire Gulf Coastal belt between the Mississippi and the Rio Grande rivers.

The method used by the writer is briefly as follows: Each sample (10–20 cc.) was treated with dilute hydrochloric acid to dissolve the carbonate compounds, and then washed free of clay content. The sand residue was then separated with the aid of bromoform (specific gravity 2.8–2.9) into light and heavy fractions. The heavy fraction was treated with a dilute solution of hydrochloric and nitric acid to remove pyritiferous and limonitic constituents. Pyrite and limonite often occur very abundantly in the heavy residues. They have little correlative value and tend to obscure the other more interesting heavy minerals. After the acid treatment, the

* Read before the South Louisiana Geological Society, April, 1939.

The writer wishes to express his appreciation to the management of the Shell Oil Company for permission to publish the data presented in this paper.

TABLE 1. *Late Cenozoic formations of the Louisiana and Texas Gulf Coast*

		Texas	Louisiana	Main Lithol. Characteristics
Quaternary	Recent	Alluvium	Alluvium	Sand, silt.
	Pleistocene	Beaumont Lissie Willis	Beaumont Lissie Citronelle (Unconformity)	Blue clay and sand. Sand and gravel. Sand and gravel.
Tertiary	Miocene—Pliocene (?)	Goliad Lagarto Oakville } Fleming	Pascagoula Hattiesburg } Fleming [Unconformity (?)]	Blue and red clay, sand Sand, clay (partly marine downdip)
		Catahoula	Catahoula	Sand, shale, limestones, partly marine (with *Heterostegina* and *Marginulina* Zones).

heavy minerals were mounted in Canada balsam and examined under the petrographic microscope for identification of the mineral species. For purposes of comparison, the approximate percentage compositions of the non-opaque minerals of each slide were established and the results tabulated. Because of difficulties in identifying opaque minerals with an ordinary petrographic microscope, no attention was paid to these other than to note abundance in comparison to the total quantity of non-opaque minerals. The average size of the heavy mineral grains also was noted, as this characteristic was found to be of some importance in grouping the heavy mineral associations.

HEAVY MINERAL ZONES OF THE GULF COAST OF LOUISIANA AND TEXAS

The following is a list of the more common heavy minerals encountered in the late Tertiary and Quaternary formations of the Gulf Coast:

I. Opaque Minerals:
Limonite
Pyrite
Magnetite
Ilmenite
Leucoxene

II. Non-Opaque Minerals:

Colorless:	*Colored:*
Zircon	Tourmaline
Garnet (mainly Almandine)	Staurolite
	Epidote
Kyanite	Hornblende
Sillimanite	Augite
Andalusite	Rutile
Barite	Anatase
	Brookite
	Sphene
	Biotite

Minerals in the non-opaque group are evidently of detrital origin with the exception of barite, which, because of the large and well-developed crystals, is considered to be of authigenic origin. The great abundance of barite encountered in

TABLE 2. *Percentage composition of heavy mineral associations in Roxana Petroleum Corporation, Hunter No. 1, Calcasieu Parish, Louisiana*

Depth of Sample	Barite	Zircon	Garnet	Tourmaline	Staurolite	Kyanite	Sphene	Epidote	Hornblende	Rutile	Anatase	Brookite	Andalusite	Size	Zone	Age
782–806	X	53	8	10	4	3	1	2	13	5	X		X	M-C	I	Pleist
1132	X	50	12	3	8	6	4	12	X	5	X			M-S		Fleming—(Oakville-Lagarto)
1173	X	60	5	5	9	7	X	6	X	8	X		X	S-M	II	
1223	X	48	11	4	9	5	2	16	X	5	X		X	S-M		
1276	X	70	1	7	12	3	X	3	X	4	X		X	M		
1323	X	75	4	6	6	2		1	X	6	X		X	S		
1350	X	63	1	11	12	7		2	X	4	X		X	M-C		
1400		58	X	12	24	4	X	X	X	2			X	M-C		
1450		75	X	10	10	1		2	X	2	X		X	S-M		
1500	X	74		7	7	5		1		6	X		X	S-M		
1585		73	2	8	3	3		3	X	8	X	X	X	S		
1631	X	39	X	27	12	9		5		7			1	M-C		
1679	X	71	X	10	5	6		X	X	8	X	X	X	S-M		
1729	X	72	1	13	6	2	1	X	X	6	X		X	S-M		
1772	X	31	21	7	7	10	1	12	8	2			1	C		
1822	X	68	X	14	5	7		1		5			X	S		
1870	X	79	X	6	6	4		X		5			X	S		
1907		79	X	3	5	X		X	X	13	X		X	S		
1938	X	62	X	11	9	4		1		13	X		X	S-M		
1995	X	59	3	5	14	14	X	X		4			1	C		
2040	X	75	X	6	8	6		X		5	X		X	M-C	III	
2090		82	3	1	1	X		2	X	11	X			S		
2093–2101	X	73	2	5	5	3		2		10	X			M		
2132–42	X	76	6	2	11	1		1		3				M-C		
2159–69		80	X	5	4	2		X	X	9	X			S-M		
2183		79	4	4	2	2	X	X		9				S-M		
2201–07	X	83	1	2	4	2	X			8	X			M		
2230–40		72	7	5	4	X		4	X	8				M-C		
2265–67	X	76	1	6	4	2		3		8				S-M		
2318–21		66	17	6	3	1		1		6	X			S		
2372–77	X	74	2	6	4	6		3	X	5			X	S-M		
2417–22	X	83	1	2	4	3		X		7	X			S		
2449	X	78	3	3	5	2		X		9	X		X	M		
2463–65	X	78	1	8	5	2		X		6				M		
2483–85	X	57	16	X	12	8	X	X		7				S-C		
2488	X	67	8	5	8	5		3	X	4	X			S-M		
2507–08	X	81	1	7	2	1		X		8				S		
2555–61	X	79	4	2	2	2		X		11	X	X		S		
2590–95	X	53	25	2	2	X	7	3		8	X	X		S		
2611–16	X	69	13	5	4	2	X	4		3				M-C		
?	X	63	12	10	5	1		X	X	9	X			S		
2748–52	X	67	16	7	5	1		2	X	2				M-C		
2777–87	X	68	12	3	5	2		3	X	7				M-C		
2812–15	X	61	17	5	5	3	X	6		3				M-C		
2838	X	64	15	5	2	1	X	X	X	12	X			S		
2888–98		56	20	5	6	4		6	X	3				M-C		
3000–01	X	71	17	4	1	1	X	2	X	3	X			M	IV	
3001–05		60	23	4	2	2	1	1	X	7	X			M		
3116–18	X	62	25	4	4	3	X	X	X	2	X			M		
3147–52	X	68	15	9	2	1	X	2	X	3				S-M		
3180–81	X	57	19	7	3	3	1	6	X	4	X			M		

TABLE 2—*continued*

Depth of Sample	Barite	Zircon	Garnet	Tourmaline	Staurolite	Kyanite	Sphene	Epidote	Hornblende	Rutile	Anatase	Brookite	Andalusite	Size	Zone	Age
3195–97	X	62	19	4	3	2		5	X	5				M-C		
3195–3203	X	58	17	5	4	3	3	5		5	X			M-C		
3278–82	X	62	19	1	1	6	3	X		8	X			S-M		
3294–97		84	7	5	X	1	2	X	X	1				S		
3366–72		70	20	2	1	3	X	X	X	4	X			S		
3395–99		65	22	4	1	2	2	X	X	3				S-M		
3455–63		64	2	10	8	11		X		5				M-C		
3489–96		78	5	1	3	1	1	1			9			S-M	V	
3520–30	X	85	5	2	3	2	X	X	X	3				S-M		
3595–3600		70	5	7	7	8	X	X	X	3	X			M		
3643–45		71	16	1	4	3	2			3				M		
3648–53	X	84	1	3	6	2	X	X		4	X			M		
3708–20		79	8	X	4	2		X	X	7	X	X		S-M		
3779–88	X	63	20	4	2	4	2	3		2				M-C		
4061–68		73	17	3	1	X	1	X	X	5				M		Fleming?
4223–27		76	19	1	1	1	X	X	X	2	X	X		M		
4287–90	X	50	38	1	3	3	3	1		1				C		
4321–24		67	12	1	5	1	1	2	10		X			S-M	VI	
4591–92		88	2	X	1	2				7	X			S		
4619–20	X	76	12	3	4	3	X	X		2	X	X		S-M		
4710–18	X	57	20	1	6	15	X	X		1				C		
4779–83		65	21	2	4	6	1			1				C		
4909–18	X	58	24	5	3	9	X		X	1		X		C		
5015–20	X	54	35	3	5	2	1	X	X	X				C		
5100–05		63	26	3	4	2	2		X	X				M		
5151–59	X	56	36	X	2	X	2		X	4				M		

S—Small C—Coarse
M—Medium X—Mineral Present (less than 1%)

sands flanking and overlying piercement-type salt domes in the Gulf Coast suggests that the formation of this secondary barite is connected with the intrusion of the rock salt (Taylor, 1938).

Table 2 shows the heavy mineral associations encountered in a well in southwestern Louisiana. This well was cored at frequent intervals, even at relatively shallow depths, and therefore offered an excellent opportunity for a study of the heavy mineral associations present in the younger Gulf Coast sediments. Even a casual glance at this table shows that there exist considerable variations in composition of the heavy mineral assemblages, particularly with respect to percentage composition. More detailed study reveals that, on the basis of these variations, distinctive mineral associations can be established and the section divided into well-characterized zones. Before describing these different heavy mineral zones, the writer wishes briefly to discuss certain petrographic and geologic factors influencing the composition of a heavy mineral association. These factors are of importance in the proper distinction of the heavy mineral zones later described. They also have an important bearing on the correlation and distribution of these zones.

PHYSICAL AND CHEMICAL STABILITY

One significant factor which largely controls the percentage composition of a heavy mineral association is the physical and chemical stability of the heavy minerals; that is, their stability against destruction during transportation and un-

TABLE 3. *Percentage composition of heavy mineral associations in Wrights et al, Felts no. 1, Jackson County, Texas*

Depth of Sample (Core)	Barite	Zircon	Garnet	Tourmaline	Staurolite	Kyanite	Sphene	Epidote	Hornblende	Rutile	Anatase	Brookite	Andalusite	Size	Zone	Age
1303–09	X	26	25	6	7	3		9	23	1	X			M-(C)	I	Pleist.
1552–53′3″	X	58	12	4	X	3	2	17		4	X	X	X	S-(M)		Oakville-Lagarto-Goliad
1555–56	X	48	22	5	6	2	4	11	X	2	X		X	S-(C)		
1566–67	X	54	18	6	4	X	2	12	X	4	X		X	S-(C)		
1573–76	X	71	14	3	X	1	1	8	X	2	X		X	M		
1609–11	X	74	14	1	2	X	2	4		3	X		X	S-M		
1660–61	X	47	35	3	5	X	1	8		1	X			S-C		
1687–88		68	15	4	1	X	1	4		7	X	X		S-M		
1689–90		64	13	4	1	1	6	6		5	X			S-M		
1715–17		74	10	3	1	X	1	6		5	X		X	S-M		
1728–29	X	59	24	5	1	X	X	8		3	X	X	X	M-C		
1877–79	X	63	14	4	2	1	1	10		5	X		X	S-M		
1881–82	A-VA	45	34	9	1	1	3	6		1			X	C		
1903–05	X	73	15	2	2	1	1	3		4			X	M-S		
1909–10	X	62	16	5	2	X	2	4		9	X	X	X	S	II	
1913–15	X	64	20	4	4	1	1	4		2			X	C		
1923–24	A	68	16	2	4	1	X	4		5				M-C		
1926–27	X	60	21	10	1	X	X	7	X	1			X	C		
1930–31	X	63	25	4	X	X	X	7		1		X	X	M		
1942–43	A	66	11	1	X		3	13		5	X		1	S		
1990–91	A	77	7	1	1	X	1	8		4	X		1	S		
2024–26	CO	71	8	5	X	X		11		5	X		X	M		
2033–35	CO	72	10	3	X	X	X	12	X	2	X		X	M-S		
2053–55	X	66	14	4	X		1	12	X	3	X		X	M-S		
2065–67	X	63	11	5	X	X	2	16		3	X			M-S		
2070–71	X	62	17	5	X	X	3	11	X	2	X			M-C		
2151–52	X	63	10	7	X	X	3	16	X	1	X		X	M		
2161–62		61	14	5	1	X	1	15	X	2	X		1	M		
2171–73		64	7	6	X	X	2	18	X	3			X	M		
2171–73		62	11	7	X	X	2	17	X	1	X		X	M		
2176–77		60	25	1		X	2	10	X	1			1	C		
2192–93	X	58	17	6	1	X	1	14	1	2			X	M-C		
2221–22	X	55	14	5	X	X	2	23	X	1				M-C		
2272–73		77	15	6	2	X	X	X	X	X				M-C		
2303–05	A-VA	73	3	11	5	4	1			3	X			M-C	III	
2542–43		85	4	4	1		X		X	6	X	X		S	&	
2544–45	X	83	11	1			X		X	5	X	X		S	IV	
2578–81	X	82	12	4	X	X	X		X	2	X			M-S		
2640–44	X	60	3	27	5	X	X			5	X			M	V	?

CO—Common
A—Abundant
VA—Very Abundant
X—Mineral Present (less than 1%)

S—Small
M—Medium
C—Coarse

der the influence of weathering conditions. Among the minerals with high physical and chemical stability in Gulf Coast sediments are zircon and rutile. These minerals were found in every sample, and, therefore, were not considered very diagnostic constituents. Their frequency relative to the other minerals ordinarily increased considerably in the finer grained sediments, as the following

heavy mineral analysis of sands belonging to the same formation demonstrates:

	GRAIN SIZE		
	Fine	*Medium*	*Coarse*
Zircon	77%	60%	25%
Garnet	11	15	27
Tourmaline	5	14	40
Staurolite	1	4	5
Rutile	6	7	3

Such variations were not regarded as having any stratigraphic significance and therefore were not given consideration in distinguishing and characterizing heavy mineral zones.

Minerals with comparatively low physical and chemical stability were found to be more valuable for correlation than the highly stable minerals. These minerals are easily destroyed during transportation and deposition, and, therefore, should be reliable for characterizing a zone in which they are common. Heavy minerals of low stability in Gulf Coast sediments are green hornblende and augite. More rare, and found only occasionally, are andalusite, sillimanite, hypersthene and biotite.

Because of relatively high physical stability, garnet holds a unique position among the heavy minerals of the Gulf Coast sediments. Since garnet seems to withstand wave action much better than most heavy minerals, it is particularly abundant in sands deposited along the beach and in shallow marine waters. Therefore an increase in the percentage of garnet in a well section was regarded as indicating nearness to marine sedimentary conditions. It is noted in table 2, that there are two such increases in garnet content in the sections studied.

Source and Origin.—During the investigation, it became apparent that certain heavy minerals common in the younger Gulf Coast sediments indicate different sources for the sediments. The presence or absence of these minerals does not appear to have any particular relation to the age of a formation. Such minerals are staurolite, kyanite, epidote and sphene. Variations in occurrence of these minerals were interpreted as indicating the presence of different sedimentary provinces. Two such provinces have been distinguished.

Few of the minerals present in these formations can be traced directly back to their original source rocks. They seem, at least in part, to have been derived from older sedimentary rocks of Cretaceous age. This is evidenced by the presence of reworked Cretaceous micro-fossils in some of the Gulf Coast formations. An exception to the above statement may be sphene and certain occurrences of hornblende and augite in the younger Miocene sands of southwest Texas. These minerals may have been derived directly from eroded tuffaceous beds and volcanic ash of the Catahoula formation, where these minerals are comparatively abundant.

DESCRIPTION OF HEAVY MINERAL ZONES

By using variations in percentage composition and previously discussed criteria for the differentiation of heavy mineral zones, it was possible to distinguish seven well-characterized zones in the Miocene to Pleistocene sediments of the Gulf Coast area of Texas and Louisiana. Beginning with the stratigraphically youngest, the characteristic features of these seven zones are briefly described. (See tables 2 and 3.)

Zone I (*Hornblende Association*).—This zone is characterized by the relative abundance of unaltered or slightly altered green hornblende. As this mineral was found in the lower zones only in very small quantities, it is an excellent marker for zone I. The other heavy minerals in this zone vary considerably in percentage and therefore furnish little assistance.

The hornblende association seems to be confined to sediments of Quaternary age. Its upper limit has not been established in the subsurface section because the first cores were usually taken well within this zone. However, as hornblende was abundantly found in recent deposits (beach sands), and in surface samples of Beaumont age, it is very likely that this mineral would also occur in the youngest

Quaternary sediments in the subsurface section. The lower limit of the hornblende zone is believed to coincide fairly closely with the Quaternary-Tertiary contact. Bailey's (1923) observations seem to support this conclusion. He reports that green hornblende is considerably more abundant in the Beaumont (Pleistocene) than in the Lagarto-Oakville (Pliocene-Miocene) formations at their outcrops in Colorado County, Texas.

The restriction of green hornblende to Quarternary Gulf Coast sediments is reasonably explained by the low chemical and physical stability of this mineral. Since the Pliocene and upper Miocene sediments of the Gulf Coast evidently consist of repeatedly reworked arenaceous material, most of the original hornblende possibly present in these beds has been destroyed during reworking.

Zone II (*Epidote Association*).—The most conspicuous characteristic of this zone is the comparative abundance of green epidote. In the subsurface section this zone is rather thin in Louisiana but thickens considerably toward the southwestern part of the Texas Gulf Coast. Examination of numerous surface samples of the younger Tertiary formations outcropping between the Guadalupe River and Sabine River, Texas, showed that this epidote association is present in beds of the Goliad-Lagarto-Oakville formations. It is assumed that this zone represents the same formations in the subsurface sections.

In the Louisiana and east Texas Gulf Coast subsurface sections, the epidote zone is an excellent correlation horizon, but it loses significance in southwest Texas (Rio Grande River) as the underlying mineral zone shows very similar characteristics.

Zone III (*Staurolite-Kyanite Association*).—The heavy mineral assemblage of zone III is characterized by a comparatively high percentage of staurolite and kyanite and a small percentage of garnet. Epidote is also present in this zone but rarely constitutes more than 5 per cent of the heavy minerals.

The staurolite-kyanite zone is well developed in the Louisiana subsurface sections, but loses its characteristic features toward southwest Texas, where it is apparently largely replaced by the epidote association. The replacement of kyanite and staurolite by epidote probably indicates the appearance of a different heavy mineral province in southwest Texas.

As the staurolite-kyanite association is considered to represent partly the epidote zone of Texas, it is concluded that in the Louisiana subsurface section this particular mineral group occurs in sediments of the same age as sediments carrying the epidote association (Pliocene-Upper Miocene). No surface samples from beds in Louisiana which correspond in age to the Goliad-Lagarto-Oakville formation of Texas have been examined to check the above conclusion.

Zone IV (*Garnet-Epidote Association*).—Zone IV contains a comparatively high percentage of garnet, particularly in comparison with the zone III. The fact that staurolite, kyanite, and especially epidote are ordinarily present indicates that zone IV has a close mineralogic relationship with the staurolite-kyanite and epidote zones. For this reason, it is believed that beds containing this garnet-epidote association in the subsurface sections are still of the same age as the Lagarto-Oakville (Fleming) formation. If abundant appearance of garnet indicates approach to marine sedimentary conditions, it follows that the exposed non-marine beds of the Lagarto-Oakville formation change to marine beds down dip, a transition which is also indicated by lithologic changes.

Zone V (*Tourmaline-Staurolite-Kyanite Association*).—Zone V is characterized by the fairly common occurrence of tourmaline, staurolite, kyanite, and by the relative scarcity of garnet and epidote.

Zone V does not seem to cover a great stratigraphic range, as it is less than 300 feet thick in most wells, but it seems to have a considerable lateral distribution. It has been identified in various wells located in an area extending from south-

western Louisiana to Nueces County, Texas.

The geologic age of this zone has not been definitely established, owing to the lack of paleontologic evidence. The close mineralogic resemblance of this association to the heavy mineral assemblage found in the exposed Catahoula formation suggests that it occurs in strata which are equivalent in age to the Catahoula. However, it is also possible that these beds are of older Fleming age, and that their detrital minerals were derived from eroded Catahoula sediments. This interpretation receives some support from the fact that there exists a well established unconformity between the Oakville (Fleming) and the Catahoula formations at the surface. It is, therefore, not impossible that some younger Catahoula beds may have been eroded farther inland and redeposited basinwards prior to the deposition of the Oakville sand.

Zone VI (Garnet-Kyanite Association).—The relative abundance of garnet is the characteristic feature of this zone. In general, the mineral composition is similar to that found in zone III, with the exception that epidote is very rare or absent and kyanite slightly more common. The heavy mineral residues of some of the coarse-grained sands encountered in this mineral zone contain as much as 40 to 50 per cent garnet (almandine). These sands suggest a beach environment where particularly favorable conditions existed for the accumulation of garnet.

The garnet-kyanite zone is well developed in the southwestern Louisiana and east Texas Gulf Coast. Toward southwest Texas (Rio Grande Valley), epidote makes its appearance, and the mineral composition becomes very similar to that of the overlying zones. Evidently a gradation similar to that noted for zone III takes place.

Zone VI occurs in subsurface beds which are assigned by some Gulf Coast geologists to the "lower marine Miocene." As the heavy mineral association found in sediments overlying the "lower marine Miocene" shows a definite affinity to the association found in outcropping Catahoula beds, it is inferred that beds carrying zone VI are of the same age as the Catahoula formation. However, in this case also, the alternative possibility of correlating the beds with the Fleming as previously discussed under zone V must be considered.

Zone VII (Tourmaline-Kyanite-Staurolite Association).—The composition of the mineral assemblage of zone VII is very similar to that of zone V. Tourmaline, staurolite and kyanite are comparatively abundant. Garnet and epidote occur rarely, or are entirely absent. As an identical association is found in beds belonging to the Catahoula formation, subsurface beds carrying the association of zone VII are considered to be of the same age as the Catahoula.

The subsurface beds underlying the section of zone VII contain an easily recognizable microfauna, which serves as a reliable marker for correlation and age determination. Petrographic study of these deeper strata therefore has not been made.

MINERAL PROVINCES OF THE GULF COAST AREA

In the foregoing section, the writer briefly discusses the characteristic features of the different heavy mineral zones which he was able to distinguish in subsurface formations of the Gulf Coastal belt of Louisiana and Texas. Boundaries between these mineral zones in most cases are fairly abrupt, as in the cases of zone IV to zone V, and zone VI to zone VII. In some instances, however, there is gradation as from zone III to zone IV. It has already been pointed out that gradations between these mineral zones also take place in a lateral direction. Changes in mineral composition were noticed down dip, but the more important gradations were found to occur along the strike. For instance, the percentage of staurolite, and particularly of kyanite, in certain mineral zones steadily increases towards the eastern part of the Gulf Coast (Mississippi River), whereas epidote becomes

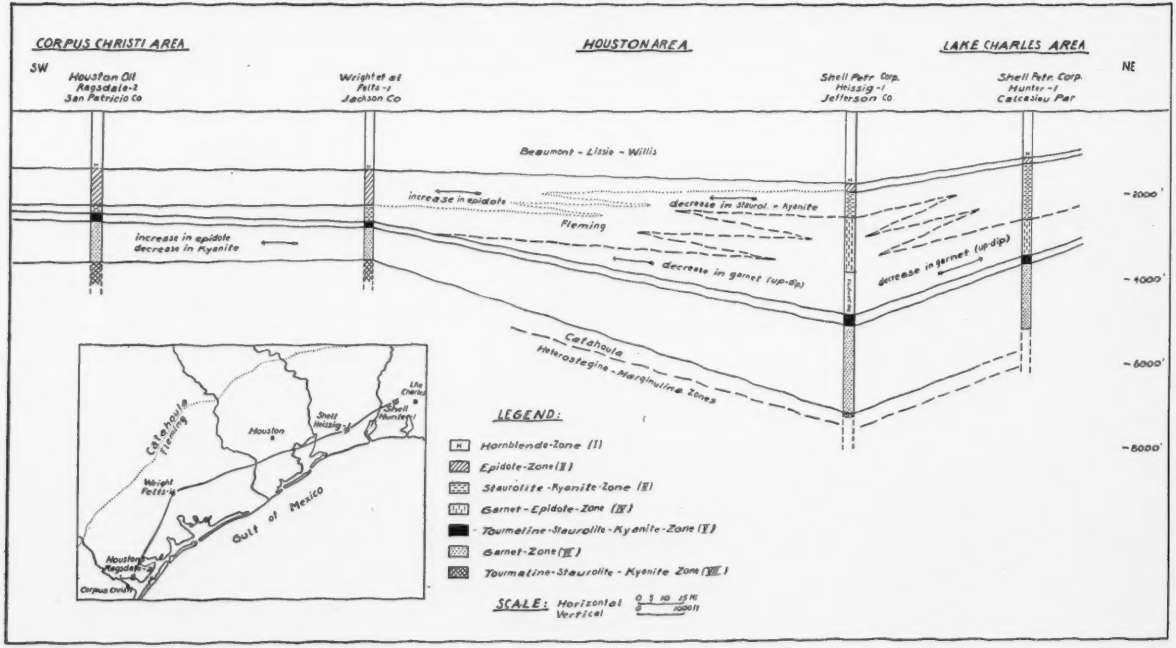

FIG. 1.—Generalized longitudinal cross-section showing correlation of heavy mineral zones between Corpus Christi, Texas, and Lake Charles, Louisiana.

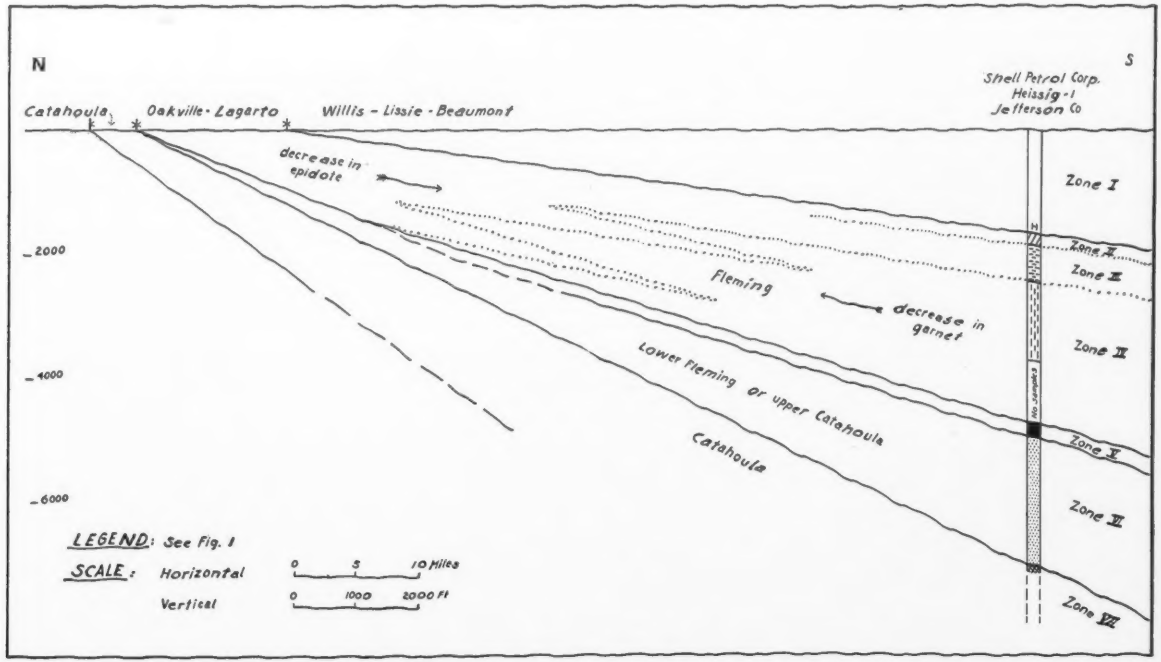

FIG. 2.—Down-dip cross-section showing heavy mineral correlation of surface and subsurface formations.

increasingly scarcer. On the other hand, epidote predominates in these mineral zones toward the Rio Grande Valley, whereas staurolite and kyanite practically disappear in that direction. The distribution of these heavy minerals thus suggests the existence of two different heavy mineral provinces in these areas. One province is characterized by the mineral epidote and to some extent by sphene, which, however, is not so common as epidote and therefore is not quite so significant. The other province is characterized by staurolite and kyanite.

Judging from the distribution of their type minerals, these two mineral provinces appear to correspond in their areal extent to the two, the Rio Grande and Mississippi embayments of the Gulf Coast area. Epidote seems to be characteristic of sediments deposited in the Rio Grande embayment, whereas kyanite and staurolite are indicative of those deposited in the Mississippi embayment.

The differentiation of heavy mineral zones in the central parts of the Mississippi and Rio Grande embayments was found to be quite difficult because of the predominance of the mineral (or minerals) typical of the respective provinces, and also because of the absence of other characteristic variations in mineral composition. However, in the area between these two embayments, that is, in the area approximately between Corpus Christi, Texas, and Lake Charles, Louisiana, the differentiation of heavy mineral zones is greatly facilitated. In this intermediate area the heavy mineral associations of the two provinces mix and interfinger, causing greater and more distinctive variations in the mineral composition. It is mainly this fact which permits differentiation of the heavy mineral zones previously described.

CONCLUSIONS

The conditions just described, as well as the correlation and the stratigraphic relations of the heavy mineral zones distinguished between Corpus Christi, Texas, and Lake Charles, Louisiana, are shown on a longitudinal cross-section which roughly parallels the coast line (fig. 1). It is evident from this cross-section, which has been slightly generalized, that during the deposition of the Catahoula formation the influence of the Mississippi heavy mineral province extended at least as far southwest as the Corpus Christi area, but during Fleming deposition, particularly during its later phases, this influence was overcome by the Rio Grande mineral province, which advanced at least as far east as southwestern Louisiana. Undoubtedly some major geologic event took place at the close of Catahoula deposition which caused this change in the source and distribution of the sedimentary material in the Gulf Coast.

Figure 2 is a generalized down-dip section showing the correlation between surface and subsurface beds on the basis of their heavy mineral content. According to this correlation the outcropping Oakville sand corresponds to sands in the subsurface which occur considerably higher in the section than generally assumed by Gulf Coast geologists. The subsurface beds containing heavy mineral zones V and VI do not seem to be represented at the surface either because of erosion or non-deposition. They must be older than the outcrop Oakville sand and younger than the outcrop Catahoula. However, the available mineralogic information is not quite sufficient to determine the exact age.

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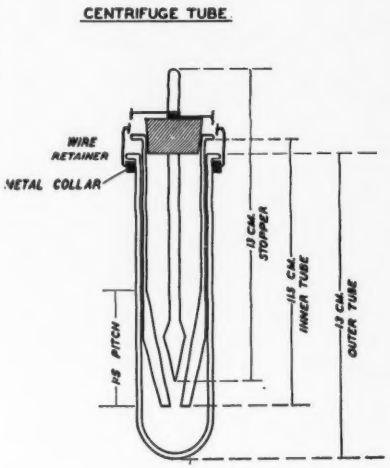
JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PAGE 136, 1 FIG., DECEMBER, 1940

FIGURE OMITTED FROM ARTICLE BY W. E. BERTHOLF, JR., JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, P. 94, AUGUST, 1940

The figure below, belonging to the article written by W. E. Bertholf, Jr., of the Soil Conservation Service, Chicago, was inadvertently omitted from the *Journal of Sedimentary Petrology*, vol. 10, p. 94, August, 1940. The article was entitled "A New Centrifuge Tube for Heavy Mineral Separation."



JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PAGE 137, DECEMBER, 1940

TREMOLITE BEARING LIMESTONE OF THE CAPITAN QUADRANGLE, N. MEX.

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ABSTRACT

A description is given of the occurrence of tremolite in a Permian limestone of the eastern part of the Capitan quadrangle. An insoluble residue analysis of a characteristic specimen shows that the tremolite makes up 5.21 per cent of the rock.

The Capitan quadrangle is near the central part of the state of New Mexico. a little to the southeast of the center of the state. The Sierra Blanca mountain range enters from the southeast and the Capitan mountain range on the east.

In the east-central part of the quadrangle, a sequence of beds of limestone, sandstone, and shale about 150 feet in thickness overlies the west end of West Capitan Mountain which forms the western end of the Capitan Range. These beds are brought to the surface by an anticline with a westward plunging axis.

The exact determination of the position of these beds in the geologic column is somewhat difficult, but they are believed to belong to the Chupedera formation of the Permian system. They are exposed in the southeastern part of T7S, R14E and the northeast one-fourth of T8S, R14E. The limestone beds constitute the most prominent and important part of the sequence.

The limestone is massive, hard, and of a dark bluish-gray color on the unweathered exposure, weathering to a lighter gray. It is for the most part unfossiliferous. Only fragments of unidentifiable fossils have been found. In many places the limestone, when struck with a hammer, gives off a strong odor of hydrogen sulphide. A noticeable feature of the limestone beds is the occurrence in many place of numerous needle-like crystals of tremolite. These are particularly noticeable on the weathered surface of the limestone, since weathering leaves them slightly raised above the surface of the rock. They are, however, quite conspicuous also on the unweathered surface because their gray color contrasts with the bluish gray of the limestone.

To determine the proportion of tremolite in the limestone, a weighed sample of a representative specimen of the tremolite bearing rock was digested in 1N hydrochloric acid; the residue was washed and dried. The residue, which contained some carbonaceous matter, was found to be 5.77 per cent of the whole by weight. The residue was then ignited in a porcelain crucible to remove the carbonaceous material and weighed again. The loss of weight on ignition was found to be 0.56 per cent of the whole. The residue after ignition was seen on a microscopic examination to consist of needles of tremolite. The proportion of tremolite in the sample examined, therefore, is 5.21 per cent by weight of the whole. The occurrence of the tremolite is not constant throughout the beds exposed, as the tremolite seems to occur only in certain places. So far as was observed, the beds bearing tremolite seem to be more numerous in the centrai part of the area exposed in the neighborhood of the axis of the anticline, but this suggestion may not be correct.

The beds in question overlie the igneous rocks of the Capitan mountains and are cut by dikes and sills of igneous rocks although dikes and sills are not as common in this part of the quadrangle as they are in other parts, particularly the southern and western parts. The tremolite is thought to have been introduced by the intrusions.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PP. 138–141, FIG. 1, TABLES 1–3, DECEMBER, 1940

SEDIMENTS TRANSPORTED BY THE BRAZOS RIVER FROM HIGH PLAINS, TEXAS

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ABSTRACT

On the High Plains, the sediments transported by the Brazos River are secured from Tertiary outcrops but at the eastern edge both Triassic and Permian rocks supply materials. The deposits in the Brazos River consist of clay, sand, pebbles, cobbles, and small boulders. Most of the boulders are pieces of "cap rock" caliche. The cobbles consist chiefly of quartz and are well rounded. The abundant minerals in the sands are quartz, biotite, muscovite, magnetite, ilmenite, garnet, epidote, tourmaline, hematite, rutile, and zircon.

The Brazos River has its source on the High Plains in the Double Mountain Fork and White River Fork (fig. 1). White River Fork extends from eastern Curry County, New Mexico, and is locally known as Running Water Creek as far as Plainview, Texas. Double Mountain Fork has its source in Bailey County, West Texas. These tributaries flow in a southeasterly direction from the High Plains as far as Stonewall County, Texas, where they merge to form the Brazos River. On the bases of relief there are three environments of deposition: the High Plains, the escarpment on the eastern edge of High Plains, and the erosional plains east of the escarpment. On the High Plains both tributary streams are intermittent; they have low gradients and the valley flats are grass covered. On the eastern edge of the High Plains is a 300-foot east facing escarpment in which the streams have cut deep, narrow valleys. East of the escarpment, about 300 feet lower than the High Plains, is an extensive erosional plain on which the streams have low gradients, wide valley flats, and braided channels.

The High Plains are Tertiary in age and were probably formed by streams that carried sediments eastward from the Rocky Mountains. These streams deposited unconsolidated materials in the textural range from clay to cobbles. Some of the surface sediments have recently been reworked by the wind. At or near the surface is a deposit of caliche. This is composed of calcium carbonate and silica and is probably a ground water deposit. Underlying the Tertiary deposits are Triassic and Permian sandstones and shales, which outcrop in the escarpment and on the lower erosional plain.

METHOD OF PROCEDURE

Samples were collected from each of the above environments, and they represent a cross-section of the stream deposits. In the laboratory 20 grams of each sample were seived and weighed. The heavy minerals, with specific gravity of 2.9 or more, were removed from each grade by means of bromoform. With the aid of a microscope the minerals were identified and counted. The light minerals, especially quartz, were classified as to the degree of abrasion into rounded, subrounded, subangular, and angular.

SEDIMENTS ON THE HIGH PLAINS

The tributary valleys of the Brazos River on the High Plains are wide, grass covered, and filling rather than eroding. These valleys probably date to Pleistocene time and were once much deeper than at present. Water wells drilled in Yellowhouse Canyon of Double Mountain Fork near Lubbock encountered pockets of pack sand up to 20 feet in thickness. Also in the same valley about

four miles northeast of Lubbock, excavations have been made to a depth of more than 20 feet. Near the bottom of these excavations bones of recent animals were found in the sand lenses. Near Plainview in the valley of White River Fork are stratified deposits of sand and gravel with a maximum thickness of 25 feet.

size-grade 20 per cent are rounded, 40 per cent sub-rounded, 30 per cent sub-angular, and 10 per cent angular.

SEDIMENTS NEAR THE ESCARPMENT

Both Double Mountain Fork and White River Fork descend from the High Plains in deep, narrow valleys, and

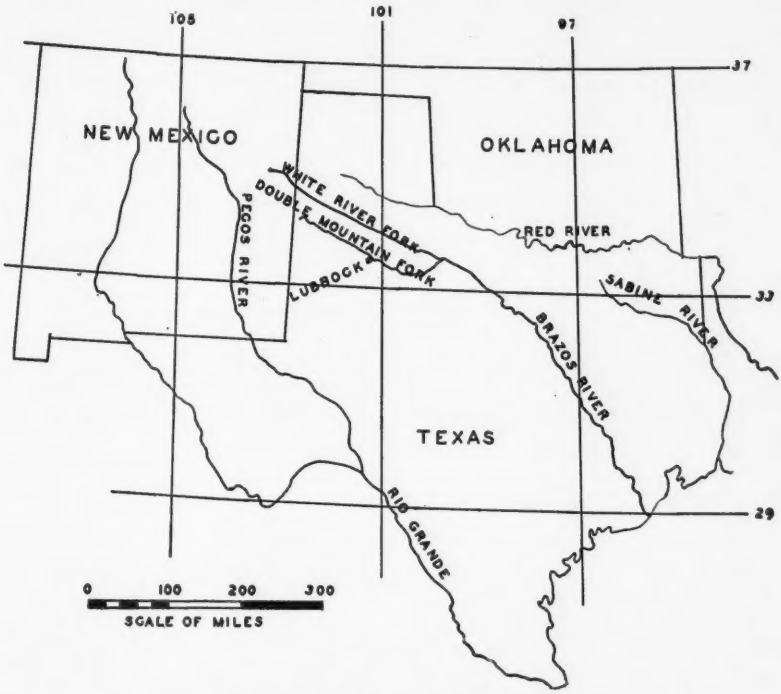

FIG. 1.—Map showing the Brazos River.

The recent deposits in the tributary valleys of the Brazos River on the High Plains are derived from rocks of Tertiary age and consist chiefly of clay with lenses of sand and gravel. The clays are more extensive on the west side of the valleys. This is thought to be due to eolian deposition. Quartz is the abundant mineral. Nearly 50 per cent of the sand is in the grade $\frac{1}{4}$ to $\frac{1}{8}$ mm. in diameter, and in this

flow from Tertiary over Triassic outcrops. The textural range of the sediments is from clay to small boulders. Most of the boulders are fragments of caliche which is exposed in the upper part of the valley wall. Gravel and sand consist chiefly of quartz with a textural range from 3 to 1/32 mm. in diameter. Most particles are in the range from $\frac{1}{4}$ to $\frac{1}{8}$ mm. in diameter. More than 60 per cent of the sand grains

larger than ¼ mm. are rounded and subrounded, angularity increases with decrease in dimensions. Most of the fine sands are iron-stained. Light minerals are quartz, biotite, and muscovite. Heavy minerals are magnetite, ilmenite, garnet, epidote, tourmaline, hematite, rutile, and zircon. The heavy minerals, with the exception of epidote, blue tourmaline, and hematite, are concentrated in the ⅛ to 1/16 mm. size. The above exceptions are most numerous in the ¼ to ⅛ mm. size. Most of the blue tourmaline is found in the deposits of Double Mountain Fork. The percentage of each of the heavy minerals in respect to the total number are magnetite 42, ilmenite 12, garnet 8, epidote 9, rose tourmaline 5, green tourmaline 3, black tourmaline 1, blue tourmaline 1, hematite 6, rutile 3, purple zircon 4, transparent zircon 4, and brown zircon 2. These sediments are derived chiefly from Tertiary deposits which form the cap rock at the eastern limit of the High Plains (table 1).

PLAINS EAST OF THE ESCARPMENT

On the plains east of the escarpment, the streams flow over Triassic and Permian strata. Deposits on the Triassic exposures consist of clay, sand and quartz pebbles. Coarse materials are deposited at the edge of the stream channel and on concave sides of meanders. Most pebbles are well rounded and less than one inch in diameter. Sand dimensions are larger than at the edge of the escarpment and the maximum size grade is ¼ to ½ mm. in diameter. Light minerals consist of quartz, muscovite, and biotite. Heavy minerals contain biotite in addition to those at the edge of the escarpment. The per cent of the heavy minerals in respect to the total number are magnetite 32, ilmenite 11, garnet 5, epidote 8, rose tourmaline 8, green tourmaline 5, black tourmaline 1, blue tourmaline 3, hematite 11, rutile 4, purple zircon 4, transparent zircon 7, and brown zircon 1. The figures show a decrease in percentages of all heavy minerals in passing from the es-

TABLE 1. *Abundance in numbers of each of the heavy minerals at edge of escarpment from 20 grams of sand*

Magnetite		1	11	110	800	180
Ilmenite			5	70	450	95
Garnet			5	25	68	35
Epidote		1	43	180	52	30
Tourmaline	rose		2	18	75	20
	green		4	18	28	16
	black			4	10	4
	blue		1	12	1	
Hematite		2	12	50	80	15
Rutile			3	15	43	20
Zircon	purple		2	6	55	36
	trans			3	70	42
	brown			2	23	16

TABLE 2. *Abundance in numbers of each of the heavy minerals on plains east of the escarpment from 20 grams of sand*

Magnetite		2	7	27	200	60
Ilmenite		1	4	15	60	19
Garnet			2	12	23	7
Epidote				17	28	15
Tourmaline	rose		4	34	52	7
	green		1	14	10	5
	black			3	2	1
	blue			2	2	
Hematite		9	22	35	30	10
Rutile			2	7	11	14
Zircon	purple			2	28	20
	trans			1	28	25
	brown				9	9

carpment with the exception of green tourmaline and rutile.

The deposits on the Permian outcrops are similar in texture and mineral content to those of the Triassic exposures, but differ in mineral abundance. There is a substantial increase in abundance of all heavy minerals (table 2).

RELATION OF HEAVY MINERALS TO THE EXPOSURES

The rocks exposed in the drainage basin of the upper Brazos are Tertiary, Triassic, and Permian. The heavy minerals in the deposits of each of the above exposures were grouped according to abundance; as very abundant, abundant, common, and rare (table 3). On the Tertiary outcrops magnetite, ilmenite, and epidote are very abundant; rutile, green tourmaline, transparent zircon, and brown zircon are common; black and blue tourmaline are rare. On the Triassic exposures magnetite is the only very abundant mineral; ilmenite is the only abundant mineral; black and blue tourmaline and brown zircon are rare; others are common. On the Permian outcrops magnetite, ilmenite, and rose tourmaline are very abundant; epidote and hematite are abundant; black and blue tourmaline are rare; and others are common.

TABLE 3. *Showing the very abundant, abundant, common, and rare minerals from the Tertiary, Triassic, and Permian outcrops*

Mineral	Tertiary	Triassic	Permian
Magnetite	VA	VA	VA
Ilmenite	VA	A	VA
Garnet	A	C	C
Epidote	VA	C	A
Rose tourmaline	C	C	VA
Green tourmaline	C	C	C
Black tourmaline	R	R	R
Blue tourmaline	R	R	R
Hematite	A	C	A
Rutile	C	C	C
Purple zircon	C	C	C
Trans zircon	C	C	C
Brown zircon	C	R	C

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PP. 142–145, FIGS. 1–5, DECEMBER, 1940

GAS PITS IN NON-MARINE SEDIMENTS

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ABSTRACT

The generation of the natural gas methane during the decomposition of organic debris is responsible for minor phenomena of sedimentation termed gas pits. Some of these are small circular pits with surrounding mud mounds formed by the escape of gas bubbles from the surface of mud bars. Larger crater-like pits are formed in submerged mud and silt bars as the result of erosion in the vicinity of active gas bubble agitation.

Numerous small mud bars were observed in headwaters of Lake Mead in November, 1937, at the conclusion of a boat trip down the Colorado River through the Grand Canyon. These bars marked the early encroachment of river mud on the great lake impounded by Boulder Dam. In addition to the features so commonly found near shorelines, such as ripple mark, mud cracks, rain drop impressions, rill marks, bird and insect tracks, small deep pits were observed in numerous places. In some cases, as shown in figure 1, these pits were the centers of concentric lines of disturbance or accretion. The small pits were formed after emergence of the mud bar as shown by their replacement of raindrop impressions.

Field studies in the headwaters of Lake Mead in November, 1939, disclosed more extensive silt bars, especially across the

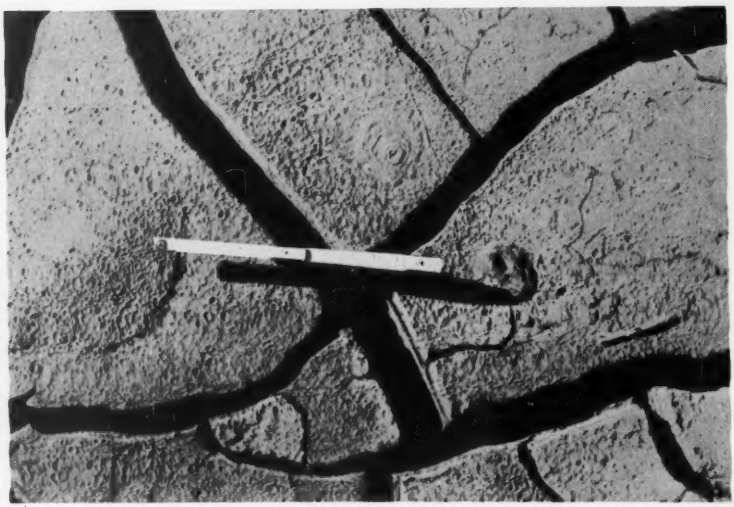

FIG. 1.—Small gas pits on mud bar at Reference Point no. 2, November, 1937. Note that the raindrop impressions were formed before the gas pits ceased activity.

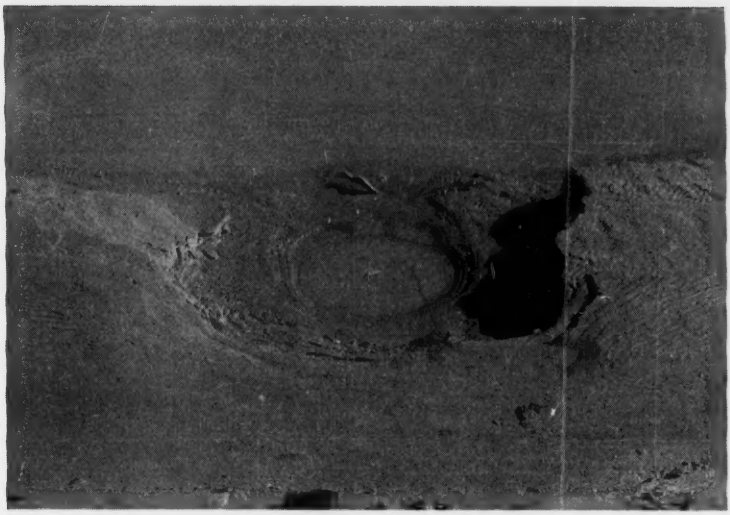

FIG. 2.—Partially emerged gas pit showing formation of strand lines by bubble-formed wavelets. The pool is about 18 inches in diameter.

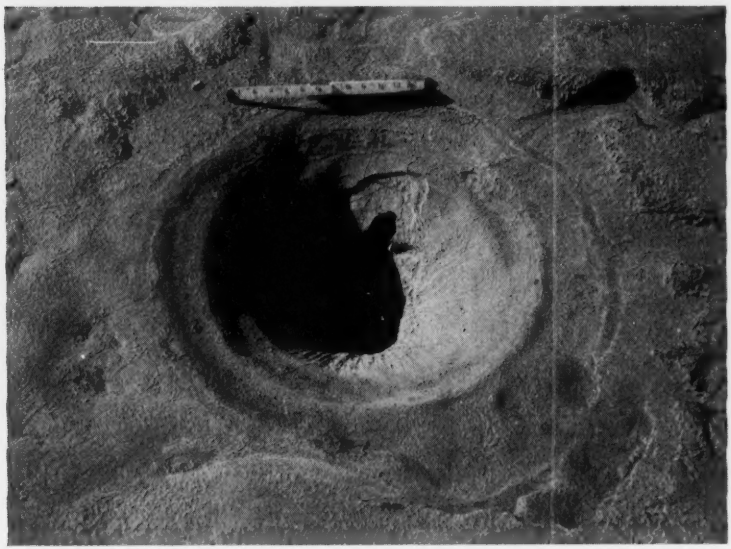

FIG. 3.—Typical steep-walled conical gas pit on mud bar at Lost Creek, November, 1939.

drowned mouths of small tributaries to the Colorado River. The head of the lake in December, 1939, was at Separation Rapids and the turbidity extended to below Waterfall Canyon some 20 miles downstream. Over a large part of this area of deposition vigorous bubbling was taking place. The escaping gas was determined to be inflammable. An inlet cut through the baymouth mud bar of Lost Creek revealed a layer of odoriferous, black, decaying vegetal matter. Decomposition of such material by bacteria is known to yield methane, nitrogen, and carbon dioxide.

The larger pits found on the mud bars are believed to have formed under water as the result of erosive action engendered by bubble agitation. The process of pit formation is probably not merely non-deposition because the organic material is buried and during the time required for large scale bacterial action to be initiated considerable compaction of the sediment would take place. Non-deposition may, however, be important in maintaining small initial gas conduits through the mud which are later increased with larger volumes of gas. When partially exposed through lowering of the water level, the bubbles form concentric waves which attack the margins of the pits forming miniature beaches, strand lines, and sometimes little cliffs. Such a gas pit is illustrated in figure 2. In some cases the gas conduits remain open after the complete withdrawal of the water. An excellent example of a symmetrical gas pit is shown in figure 3. Larger pits are formed when several gas conduits are adjacent as illustrated by figure 4. If the water is withdrawn uniformly, a pit tends to possess a symmetrical inverted conical shape. If the water stands in the pit, the upper part of the cone may be broadened by the miniature wave attack.

Gas pits vary greatly in size. Some were observed having a diameter of a

FIG. 4.—Large emerged gas pit with multiple vents showing well developed strand line features in the upper part as the result of long continued stand of water at that level.

FIG. 5.—Gas pits in mud bar in various stages of obliteration. Lost Creek, November, 1939.

fraction of an inch; the largest had a diameter of 6 feet and a depth of 4 feet. The average size noted was about 1.5 feet in diameter and 8 inches in depth.

Gas pits are not enduring features and after emergence may be expected to be rapidly destroyed by rain wash. In later stages of filling the shallow concavity could only be recognized as a gas pit if intermediate stages were present. Figure 5 illustrates a number of hollows doubtless originating as gas pits. If similar hollows are found in lithified sediments it may be suspected that they originated in shallow water where sediment rich in organic debris was being deposited. However, they do not necessarily indicate deposition in an environment of humidity because the organic materials may have been transported to an arid region, such as the lower Grand Canyon in the case described.

Gas pits differ from mud volcanoes which are developed by mud deposits about gas vents on the earth's surface inasmuch as they are usually smaller and predominantly excavations. They are associated with the lower gas pressures of bacterially generated marsh gas rather than with the higher pressures of oilfield or volcanic gases.

Spring pits have been described (Quirke, 1930) on the shores of Maple Lake near Parry Sound, Ontario. These were formed in a sandy submerged beach by numerous water outlets. They were observed to be usually under 2 feet in diameter and 6 inches in depth. They appear to be more shallow and irregular than gas pits.

ACKNOWLEDGEMENTS

The writer wishes to thank Mr. E. D. McKee, who was a member of the 1937 Colorado River expedition, for criticism of the manuscript.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 3, PP. 146–147, DECEMBER, 1940

STYLOLITES

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In his article on stylolites in the August, 1939 number of the *Journal* (bottom of page 48 and top of page 49), Shaub says: "for stylolites to develop according to the solution-pressure theory, the natural processes of deposition would have to deposit systematically on the opposite sides of the 'bedding plane, lamination plane or crevice' a sharply bounded pattern of 'differentially soluble' limestone in such a manner that the more and the less resistant parts stand opposite each other in order that stylolites start their development at some geologically later date. It is, indeed, difficult to understand how sedimentary processes could deposit such very fine-grained materials (or how later processes could rework them) so as to produce such a sharply defined arrangement of more and less soluble material."

I am not sure that I understand just what the author is objecting to, but two factors seem to be involved. One is that he considers it difficult to conceive of a sedimentary process by which materials respectively more and less soluble should, in an intricate pattern, everywhere come to lie opposite each other. The answer to that seems to me to be that in order to produce the projections on a stylolitic surface, it is not necessary that there be a difference of solubility on the two faces of every projection or depression. Projections would start where there was a difference of solubility between the two opposing faces, but in the intervening areas the solubility of the two faces might be the same and yet solution along the contact might continue and produce a highly irregular surface. Projections, once having originated from a difference of solubility between the two faces over a given area, might be preserved under conditions of equal solubility on the two faces of that area. But in view of such factors as the differences in structure and composition of the shells of different organisms, and of differences in solubility of crystalline substances in different crystal directions, it does not seem difficult to conceive of conditions that would produce closely spaced areas of different solubility along a contact surface.

Fineness of grain and consequent degree of homogeneity of a rock, which seems to be the other factor over which Shaub is concerned, would be a modifying factor, but in most stylolites that I have seen the spacing of the projections has not appeared different in scale from the grain of the rock. Certainly, the spacing of some of the projections illustrated in the lower part of Shaub's figure 4, page 56, is close enough to conform to a very fine grain.

Shaub's interpretation (p. 55) of the truncation of fossil shells along a stylolitic seam as the result of shear by soft sediment flowing past them along a steep stylolitic surface does not seem adequate to account for such truncation as I have illustrated in figure A, plate XIII of Professional Paper 146 (Goldman, 1926), where the stylolitic surface is nearly horizontal. Moreover, this appears to involve the cast of a shell, not the shell itself, an indication that the stylolite was formed after the consolidation of the rock. It is also difficult to account for the minutely jagged character of the stylolitic contact along the edges of these large pellets or fossil casts on the assumption that the material was soft when the stylolitic surface formed. Flow of soft sediments past each other would presumably produce smooth surfaces (Bradley and Pepper, 1938).

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It is, furthermore, much easier to conceive of a minutely jagged surface with many long, thin, needle-like points, like that illustrated in Shaub's figure 4, page 56, forming in indurated material than by injection of soft material into similar soft material.

I may say that I am not convinced that the form of stylolitic surfaces is entirely due to differential solution. From what I have seen of flow, in sediments that must have been consolidated, I am ready to believe that some adjustment between more rapidly advancing and less rapidly advancing parts might take place by flow in the consolidated rock without leaving any readily recognizable effects. This may explain such phenomena as the diverging striations illustrated in Shaub's figure 5, page 56.

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O. C. Marsh, Pioneer in Paleontology, by Charles Schuchert and Clara Mae LeVene. 541 pp., 30 pls., 33 figs. Cloth. $5.00. New Haven, Yale University Press. (1940.)

This is one of the best documented biographies that has been written; it is comprehensive, profound and honest. It should, in my opinion, be a *must* book on every scientist's library. For the paleontologist, the authors have done an invaluable piece of work in writing the book. One has only to page through the volume to get an idea of the amazing amount of diligent and tedious research which has been crowded into its pages.

Those who are not paleontologists may find that the book is a bit heavy and wearisome reading. But, that is largely because the volume is thickly footnoted and fluently interspersed with direct quotations from Marsh and his associates. To the paleontologist, these quotations and footnotes are the real meat of the work. However, they tend to slow the reading, and the non-geologist finds himself skipping over passages which are in smaller type in order "to get on with the story." The book is not depressing or dull, but decidedly an inspirational work. It contains the purging quality that lies in the presentation of truth.

The authors introduce young Marsh with an excerpt from Emerson that "every man is a quotation from all his ancestors." The book moves through his young manhood and his life as a student at Andover and Yale colleges, taking him then to the Sheffield Scientific school and to Europe.

Successive chapters in the biography are devoted to Marsh's uncle, George Peabody, to the Yale expeditions of 1870–1873, and to the Black Hills with the expedition of 1874, which brought Marsh into the public prominence and later involved him in the famous Indian affairs scandal. This investigation, led by Marsh, into Indian affairs resulted in a general housecleaning in the Indian bureau and the Department of Interior. But, like many crusading efforts, the publicity and public criticism did not do Marsh's scientific reputation any good.

The second half of the book is given over to Marsh's bone diggers, his ideas on evolution, the laboratory assistants of the famous paleontologist, his home and "his sunset years." Attention is also focused on some of the prehistoric animals studied by Marsh; pages are given to his amazing discoveries of flying reptiles, primitive mammals and colossal dinosaurs. One of the best parts of the book is the extensive bibliography and the well prepared index.

Quotations and excerpts from the works of Marsh included in the biography, show that the paleontologist also had the ability to write and to present a colorful account of some of his experiences. Some of Marsh's accounts of his various trips are as spirited as any rootin', tootin' western story. Such as the time when he was caught in a stampede of wild buffalo. He wrote, as quoted in the biography, in part: "to my amazement I saw that the main herd, alarmed by the shots of my comrades, had started and was moving rapidly southward. I saw also what I had not before surmized; that in my eagerness I had pushed well into the herd without noticing it, and as the great mass of animals in the rear started, they began to lap around me, and I would soon be enclosed in the rapidly moving throng liable at any moment to be trampled to death if my pony should fail me. My only chance to escape was evidently to keep moving with the buffalo and press toward the edge of the herd, and thinking thus to cut my way out, I began shooting at animals nearest to me to open the way. Each shot gave me some gain, as those near pushed away, and when one went down, others stumbled over him. The whole mighty herd was now at full speed, the

earth seemed fairly to shake under the moving mass, which, with tongues out, and flaming eyes and nostrils, were hurrying onward, pressed by those behind, up the broad valley which narrowed as it approached the higher land in the distance. . . . "

In all that goes to make a good biography, *O. C. Marsh, Pioneer in Paleontology* is interesting, particularly for the elaborate use of pictures, which contribute largely to the high caliber of the book. There are not only reproductions of fine, old prints, but rare group pictures which must have been difficult to obtain. For instance, there are those of various Yale expeditions, those of Red Cloud and Dr. Marsh, and those of Marsh together with his scientific associates. The most colorful of the pictures are the pen and ink cartoons which appeared in Harper's New Monthly Magazine and illustrated some of Marsh's experiences on these expeditions.

The title of the book is well chosen for O. C. Marsh was a pioneer in paleontology and really could be referred to as the father of American vertebrate paleontology. Because he set the pace in this science with his ingenuity, enthusiasm and keen insight, Dr. Schuchert, who knew him personally, felt that " . . . an account of Professor Marsh must be written to give future generations of geologists and other scientists a true picture of this great paleontologist, with no attempt to minimize the unfortunate aspects of his career, but with strong emphasis on his far reaching achievements in vertebrate paleontology. He was, indeed, among the greatest scientists which America has produced. . . . "

Sincerely, fairly and with an abundance of homely detail, Dr. Schuchert and Miss LeVene reveal the personality of a man, who is not only great as a scientist, but outstanding as an American citizen, believing candidly in the individual and in right for right's sake. Marsh is unreliable and a procrastinator. He is undependable, nervous, ingenious and brilliant. His is a vigorous personality and the authors have done a good job of translating this personality from records and reminiscences to the pages of their book. The biography holds, without question, one of the best character drawings that has been done by any contemporary popular writer.

Dr. Schuchert and Miss LeVene are not creative writers, but they do have the ability to present a theme in a pleasant style even though this style could be more flowing, less verbose. One has the feeling that every detail is important, no matter how small, and that the authors want to give the reader every fact, no matter how insignificant, about the famous paleontologist. The book is definitely not a textbook, but it certainly contains material which every scientist will want to read and there is no doubt that it will be on the supplementary reading lists of many colleges.

This biography was not written for the general public but that does not mean that the public would not be interested in it. For in this biography, the authors give the reader an insight into the birth of a profession, that of vertebrate paleontology. They introduce the reader to this country when it was still "the wild west" on the other side of the Mississippi River. Many famous persons are made to live in the numerous chapters including Charles Darwin, Thomas Huxley, A. Agassiz, Benjamin Silliman, E. D. Cope, who carried on a long feud with Marsh, Buffalo Bill, Brigham Young and John Bell Hatcher, Marsh's most outstanding collector of fossils.

Many geologists, without question, will add this biography to their libraries as a companion to H. F. Osborn's *Cope, Master Naturalist* and W. B. Scott's *Memoirs of a Paleontologist* for the three books effectively give a good cross section of the growth of one division of the geological sciences in America. This much is certain, *O. C. Marsh, Pioneer in Paleontology* is the story of a great personality closely interwoven with the history and people of the United States over the last half of the nineteenth century.

MARVEL Y. INGS

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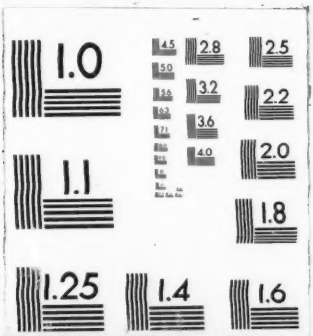
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